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Performance analysis of photovoltaic systems: A review

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ABSTRACT

In this paper, a thorough review of photovoltaic and photovoltaic thermal systems is done on the basis of its performance based on electrical as well as thermal output. Photovoltaic systems are classified according to their use, i.e., electricity production and thermal applications along with the electricity production. The application of various photovoltaic systems is also discussed in detail. The performance analysis including all aspects, e.g., electrical, thermal, energy, and exergy efficiency are also discussed. A case study for PV and PV/T system based on exergetic analysis is presented.

Contents

1. Introduction

Energy is a key item in our relations with the environment. Energy consumption determines how much and how severely we can affect our environment, and how damaging or healing our

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Nomenclature

A	Area (m^2)
A_c	Area of a solar cell (m^2)
E	Electrical power (W)
$\dot{E}n$	Total Energy (W)
$\dot{E}x$	Exergy (W)
$\dot{E}x_{solar}$	Exergy of solar irradiance (W)
FF	Fill factor (dimensionless)
h_{ca}	Combined (including convection and radiation) heat transfer coefficient from solar cell to ambient air (W/m^2 K)
H	Water delivery head (m)
I	Current (A)
I_m	Current at maximum power generation (A)
I_{sc}	Short-circuit current (A)
N_{MP}	Number of modules in parallel in the PV generator
N_{MS}	Number of modules in series
N_p	Number of cells in parallel in the PV module
N_S	Number of cells in series in a module
PR	Performance ratio
P_M	Maximum electric power of the generator (W)
P_W	Input electric power of the motor pump unit (W)
Q	Water flow rate (m^3/h)
$\dot{Q}$	Available thermal energy (W)
$\dot{Q}_{solar}$	Exergy from the heat (W/m^2)
S_T	Hourly measured total solar irradiation (W/m^2)
S_{STC}	Total radiation at standard test condition (W/m^2)
T_0	Reference ambient temperature = 20 °C (293 K)
T_{amb}	Ambient air temperature (°C)
T_{cell}	Photovoltaic cell temperature (°C)
T_f	Temperature of flowing air (°C)
T_{sun}	Sun temperature (5777 K)
v	Wind velocity just above photovoltaic surface (m/s)
V	Voltage (V)
V_m	Voltage at maximum (actual) power generation (V)
V_{oc}	Open-circuit voltage (V)
$Y_{a,d}$	Daily array yield (h/day)
$Y_{a,m}$	Monthly average daily array yield (h/day)
$Y_{f,d}$	Daily final yield (h/day)
$Y_{f,m}$	Monthly average daily final yield (h/day)
$Y_{r,d}$	Daily reference yield (h/day)

Greek letters

η	Energy efficiency (%)
η_0	Electrical efficiency under standard test condition (%)
η_{Carnot}	Carnot cycle efficiency (%)
η_{cell}	Solar cell efficiency (%)
η_{pce}	Electrical efficiency, power conversion efficiency (%)
η_f	Energy saving efficiency (%)
ψ	Exergy efficiency (%)
ψ_e	Electrical efficiency (%)

Subscripts

AC	Alternate current
CR	Charge regulator
d	Daily
DC	Direct current
e	Electrical
EL	Electrolyzer
IN	Inverter
m	Monthly
Mis	Mismatch
MP	Motor pump
PV	Photovoltaic
PV/T	Photovoltaic/thermal
sys	System
S_T	Solar radiation
th	Thermal
total	Total

interactions with it are. Its role is vital for our life and for our economy. Thermal form of energy also plays an important role in human life as it can generally be utilized in the form of either high-grade (high-temperature) or low-grade (low-temperature). Solar photovoltaic and thermal applications appear to be one of the potential solutions for current energy needs and to combat greenhouse gas emissions.

Clean energy generation has become increasingly important with the growing significance of environmental issues, solar energy is a clean energy source, but it is intermittent in the nature and does not persist continually for long durations at a given location. In 1839, Becquerel first observed the photogalvanic effect and suggested that sunlight can be converted directly into electricity. Then, Adams and Day found the photovoltaic properties of selenium in 1876. Planck proposed the quantum nature of light in 1900. Thereafter Wilson gave the quantum theory of solids, relating the photon and the properties of solids in 1930. Mott and Schottky developed the theory of the solid state diode after a decade. In 1949, Bardeen et al invented the bipolar transistor (see Ref. [1]). In 1954, the first solar cell that had an efficiency of 6% was developed by Chapin et al and after four years these solar cells were used on the Vanguard I orbiting satellite (see Refs. [1–4]). After the development of PV technology and its use in the space applications, it is now being used for terrestrial applications for example rural electrification, solar water pumping, space heating, etc.

Fossil fuel-based electricity generation often must supplement PV systems. In many studies there has been the attempt to address the need and potential solutions [5]. During the last decade, PV applications have increased and extended to industrial use in some countries. The clean, renewable and in some instances economic features of PV systems have drawn attention from political and business decision makers and individuals. Advances in PV technology have also led to increased usage.

Photochemical energy converting systems, which include photoelectric devices and biological photosynthesis, operate by collecting a fraction of the radiation within some range of wavelengths. Photon energies greater than the cutoff, or band-gap energy are dissipated as heat, and photons with wavelengths longer than the cutoff wavelength are not used by PV devices. Some theoretical thermodynamic limits on the efficiency of photochemical solar energy conversion have been investigated by Ross and Hsiao [6]. Wurfel [7] has also discussed thermodynamic limitations on solar energy conversion, based on an entropy concept, and calculated the upper efficiency as 0.86 for maximally concentrated solar irradiation. Petela [8,9] has evaluated the exergy of undiluted solar radiation and also given the definition of various exergy components including buoyant, altitudinal, gravitational and mechanical exergy. Smestad [10]

has examined concepts of hot carrier and light converter, indicating that electrons are ejected not only as heat but also as light. The Carnot factor in PV cell theory has been studied by Landsberg and Markvat [11]. They obtained an expression for open-circuit voltage which is equal to the bandgap multiplied by the Carnot efficiency. Some physical and chemical principles of photovoltaic conversion are presented by Bisquert et al. [12]. They found the relation between chemical potential and open-circuit voltage of a PV cell to be dependent on Carnot and statistical factors. Markvart and Landsberg [13] also discuss the thermodynamics and reciprocity of solar energy conversion by considering PV, photochemistry and photosynthesis.

Sahin et al. [14] and Dincer and Rosen [15] have investigated thermodynamic aspects of renewables for sustainable development. They explain relations between exergy and sustainable development. The energy conversion factor of a solar photovoltaic system sometimes is described as the efficiency, but this usage sometimes leads to difficulties. The efficiency of a solar photovoltaic cell can be considered as the ratio of the electricity generated to the total, or global, solar irradiation. In this definition only the electricity generated by a solar PV cell is considered. Other components and properties of PV cells, such as ambient temperature, cell temperature and chemical components of the solar cell are not directly taken into account.

Sahin et al. [16] have done a comprehensive thermodynamic analysis (including exergy analysis) of a photovoltaic cell using the various properties namely chemical component of photovoltaic cell as discussed above.

Jones and Underwood [17] have studied the temperature profile of photovoltaic (PV) module in a non-steady state condition with respect to time. They performed experiments for clear as well cloudy day condition and observed that the PV module temperature varies between 300 and 325 K (27–52 °C) for an ambient air temperature of 297.5 K (~24.5 °C). The thermal energy associated with PV module may either be removed (carried away) by air or water. When the thermal energy requirement is integrated with photovoltaic (PV) module, it is referred to as hybrid PV/T system. Hybrid PV/T systems may find applications for: (i) air heating (e.g., Refs. [18–26]) and (ii) water heating (e.g., [25,27–33]).

Chow [30] has carried out the analysis of PV/T water collector with single glazing in a transient condition. The tube underneath flat plate with metallic bond collector was used. He observed that photovoltaic conversion efficiency at the reduced temperature is increased by 2% at mass flow rate of 0.01 kg/s for 10,000 W/(m^2 K) plate to bond heat transfer coefficient. An additional thermal efficiency of 60% was also observed. For water heating under natural mode of operation, Huang et al. [34] have studied experimentally the unglazed integrated photovoltaic and thermal solar system (IPVTS). They observed that the primary energy saving efficiency of IPVTS exceeds 0.60 which is higher than that for a conventional solar water heater or pure PV system. Kalogirou [32] has studied the monthly performance of unglazed hybrid PV/T system under forced mode of operation for climatic condition of Southern Cyprus and observed an increase of the mean annual efficiency of PV solar system from 2.8 to 7.7% with thermal efficiency of 49%, respectively. Similar study has also been carried out by Zondag et al. [33]. They have referred to hybrid PV/T as a combi-panel that converts solar energy into both electrical and thermal energy. The electrical and thermal efficiency of combi-panel were reported as 6.7 and 33%, respectively.

Sandnes and Rekstad [28] have observed the behavior of a combined photovoltaic/thermal (PV/T) collector which was constructed by pasting single-crystal silicon cells onto a black plastic solar heat absorber (unglazed PV/T system). They recommended that the combined PV/T concept must be used for low temperature thermal application for increasing the electrical efficiency of PV system, e.g., space heating of a building. Zakharchenko et al. [29] have also studied unglazed hybrid PV thermal (PV/T) system with a suitable thermal contact between the panel and the collector. They have proved that the areas of PV panel and collector in PV/T system need not be equal for higher overall efficiency. To operate PV module at low temperature, PV module should cover the low temperature part of the collector (at cold water inlet portion). Further, unglazed hybrid photovoltaic/thermal with booster diffuse reflector was integrated with horizontal roof of a building by Tripanagnostopoulos et al. [25]. They suggested that PV/T system with reflector gives clearly higher electrical and thermal output. They have also studied the performance characteristic of PV/water and PV/air systems. Infield et al have derived an overall heat loss coefficient (U) and thermal energy gain factor (g) for ventilated vertical photovoltaic (PV) module and double glazed window (PV facades) [24]. The steady state analysis was used to determine ventilation gains and transmission losses in terms of irradiation (solar radiation) and various heat transfer process involved in facades. He observed that the ventilated facades ensure that the electrical efficiency of PV module is improved due to low temperature (generally below 45 °C). Hegazy [23] and Sopian et al. [35] investigated glazed a PV/T air system for single and double pass air heater for space heating and drying purposes. They have also developed a thermal model for each system. They observed that thermal energy for glazed PV/T system has increased with lower electrical efficiency due to high operating temperature. Further, Coventry [36] has studied the performance of a concentrating photovoltaic/thermal solar collector and concluded that an overall thermal and electrical efficiency of PV/T concentrating system are 58 and 11%, respectively. This gives a total efficiency of the system as 69%. Joshi and Tiwari [37] observed an instantaneous energy and exergy efficiency of PV/T system varies between 55–65 and 12–15%, respectively for cold climatic conditions of Srinagar, India. Joshi and Tiwari [38] and Joshi et al. [39] have also done the experiments on PV/T air collector for climatic conditions of New Delhi, India and found an overall thermal (energy) and exergy efficiency about 50 and 14%, respectively. Tonui and Tripanagnostopoulos [40,41] compared unglazed and glazed PV/T air collector with a simple air channel (duct) attached behind the PV module, a thin (flat) metal sheet (TMS) placed in the middle of the air channel and fins attached to the opposite wall of the air channel and found that latter methods are better than the previous methods in order to remove heat from the PV surface. They also recommended that the modified systems can effectively be used in solar chimneys to operate effectively for natural ventilation to building to achieve space cooling during summer or heating during winter (with closed loop air circulation) and hence suitable for building integration with a considerable contribution to the thermal and electrical demand of the building. Further, additional glazing improves the heat production but lowers the electrical efficiency of a PV/T air collector, they added similar to the comments of Charalambous et al. [42].

Tripanagnostopoulos [43] made some more improvements in the existing system by introducing an unglazed PVT/dual system with both water and air cooling modes (Fig. 1a) and found that by attaching water tubes at the back surface of PV gives better thermal efficiency. By adding a thin metal sheet (TMS), fins (FIN) and a combination of TMS with ribs (RIB) (TMS at the centre of the air duct and RIB at the opposite side of the PV surface) as shown in Fig. 1b–d, respectively, he compared the three modified systems with the reference PVT/dual (water tube attached at back surface (Fig. 1a)) system and found a significant increase in thermal efficiency for the air heat extraction, which is respectively approximately 23, 33 and 36% higher for the said systems described above. Use of an additional booster diffuse reflector (REF), as shown in Fig. 1e further improves electrical performance

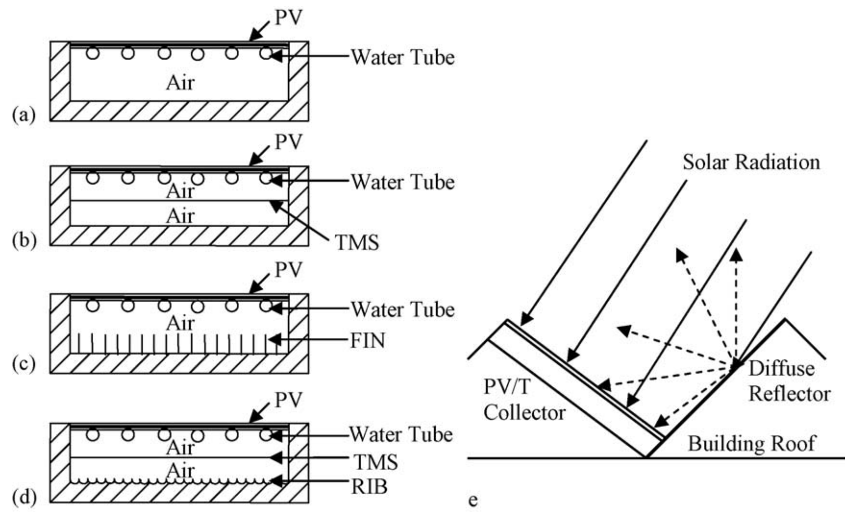

Fig. 1. Cross-sectional view of (a) PV/T dual system, with (b) the thin metal sheet (TMS), (c) the fin on opposite air duct wall (FIN), (d) the combination of TMS and ribs on the opposite air duct wall (TMS/RIB) and (e) PV/T collector using a diffuse reflector (modified from Ref. [43]).

by 12% for the low (about 0 °C) operating temperatures, with electrical efficiency of 16.5 and 18.5% for the typical PV and the PV with booster diffuse reflector, respectively. This increase in electrical performance percentage is more significant for higher (about 55 °C) operating temperatures, as it happens usually in PV/T collectors, thus the electrical performance can be higher by about 18% as electrical efficiency is 13 and 11%, respectively for the PV and the PV with booster diffuse reflector systems. The comparison of the various combinations discussed above is given in Table 1 in terms of thermal efficiency. A comparison of electrical efficiency with and without a reflector is also given in the same table.

2. Photovoltaic systems

The photovoltaic systems, as shown in Fig. 2, can be classified according to their use and applications. These systems can broadly be classified into two types: (1) photovoltaic (PV) systems and (2) photovoltaic thermal (PV/T) systems. The first type can further be classified into space applications, stand alone PV systems, grid connected PV systems, photovoltaic hydrogen production systems and miscellaneous small scale applications where as the second type can further be classified as PV/T air collector and PV/T water collector systems and others. Further, the stand alone PV applications can be classified into two, agricultural water pumping and community or rural electrification. The PV/T air collectors can be used for agricultural greenhouse drying and space or room heating applications where as the water collectors can be used for domestic and industrial water heating, water distillation (hybrid solar stills), space heating etc. Some other miscellaneous applications of the PV and PV/T systems are also described later in this section. Now we will refer to each application one by one.

2.1. Photovoltaic (PV) applications

The photovoltaic applications can be beneficial where ever the electrical energy is needed. Based upon the requirement of electrical energy various systems came into the existence. The photovoltaic technology has always had an upper edge on other technologies as it is pollution free and it uses solar energy that is freely and immensely available. Another advantage with the PV technology is that it does not emit any greenhouse gases during the operation and hence is environment friendly. The intermittency of solar radiation can be a limitation to the technology as it cannot supply electricity continuously during the off sunshine periods, but this problem can be resolved by using battery storage. However, there is a need to understand the application of this technology to make it feasible for its users. For example, to water a field, a farmer can use a solar water pumping system during day time and get benefit from the technology as he does not have to worry about the unwanted load shedding or power failure as he would be independent of the grid electricity. Another example could be solar street lighting; the electricity converted by PV panels during the sunshine hours can be stored in a battery and can be utilized to power the street lights in the off sunshine periods. Here, in this

Table 1
Efficiency equations of the PV/T/dual collectors.

System	Thermal efficiency	
	Water	Air
PV/T/dual-TMS	$\eta_{th} = 0.556 - 12.824\Delta T/S_T$	$\eta_{th} = 0.391 - 8.484\Delta T/S_T$
PV/T/dual-FIN	$\eta_{th} = 0.553 - 12.981\Delta T/S_T$	$\eta_{th} = 0.423 - 8.488\Delta T/S_T$
PV/T/dual-TMS/RIB	$\eta_{th} = 0.545 - 12.771\Delta T/S_T$	$\eta_{th} = 0.434 - 8.933\Delta T/S_T$
PV/T/dual-TMS + REF	$\eta_{th} = 0.662 - 11.969\Delta T/S_T$	$\eta_{th} = 0.548 - 10.222\Delta T/S_T$
PV/T/dual-FIN + REF	$\eta_{th} = 0.651 - 11.731\Delta T/S_T$	$\eta_{th} = 0.595 - 10.286\Delta T/S_T$
PV/T/dual-TMS/RIB + REF	$\eta_{th} = 0.651 - 11.870\Delta T/S_T$	$\eta_{th} = 0.623 - 11.133\Delta T/S_T$
PV/T/dual	$\eta_{th} = 0.475 - 11.671\Delta T/S_T$	$\eta_{th} = 0.319 - 7.471\Delta T/S_T$
Electrical efficiency		
PV module	$\eta_e = 0.166 - 0.001T_{PV}$	
PV module + REF	$\eta_e = 0.185 - 0.001T_{PV}$	

Source: Ref. [43].

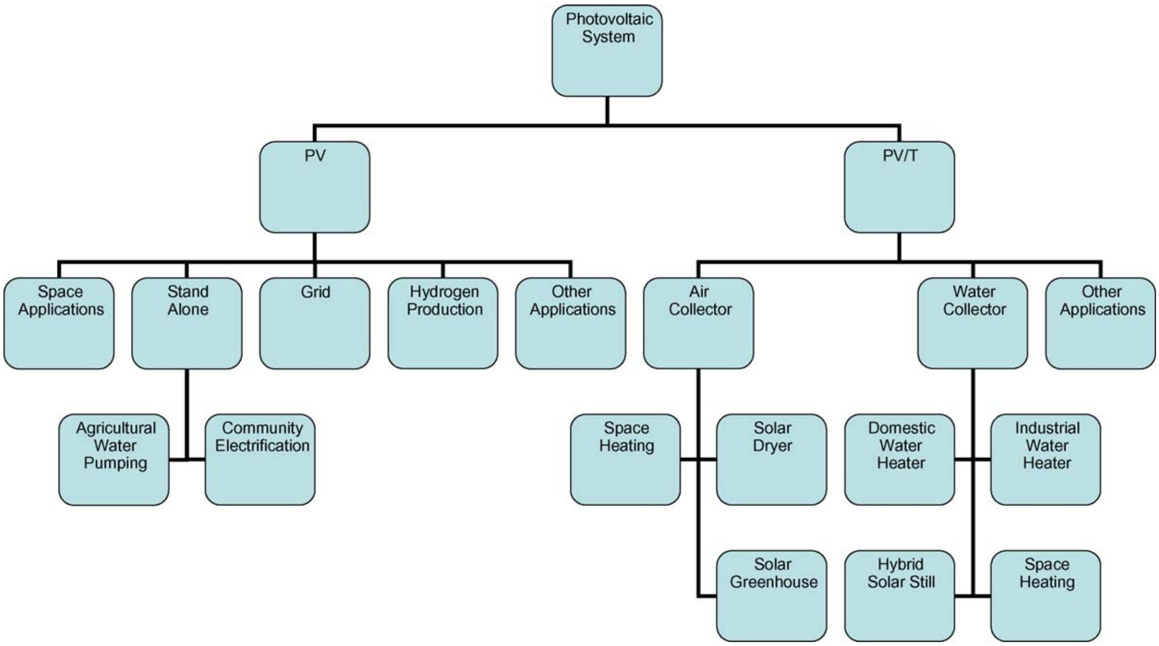

Fig. 2. Classification of PV systems based on their applications.

section, we are discussing various photovoltaic applications based on their performance in terms of efficiency.

2.1.1. Space applications

Probably this was the very first application of photovoltaic that it was started in 1958 using in space craft and satellites [1–4]. The efficiency of the PV panels was 6%. The light weight PV panels were used to power the space craft/shuttle for their electrical demands in space. In space PV cell technology, GaAs-based cells are now mature and space qualified. High efficiency thin Si cells give good and impressive performances when price, weight, maturity, and efficiency are balanced. Table 2 gives typical performances of cells in terms of efficiency (for 28 °C, air mass zero (AM0) and beginning of life (BOL) conditions) [44]. Price is a variable that depends on many parameters like, technology evolution, manufacturer policy, geographic location for getting into the market, mode of transportation etc. and hence it is difficult to predict, so, cost information is only representative in Table 2. Quadruple junction cells give better efficiency, however they are not space qualified yet and are in an extensive research period, presently.

With the increase in cell temperature the cells efficiency decreases significantly. Concentration of solar radiation on the PV panel, though, gives higher electrical output but reduces cell efficiency as it is responsible for additional heat inside the cell. This is one of the draw back of concentration that it leads to conversion efficiency loss [44]. Table 3 gives an estimate of the cell efficiency at 58 °C (~rigid array, no concentrators used ($C = 1$)) and 100 °C (~concentration array ($C = 1.75$)) [44]. GaAs-based cells give a lower loss which shows that it is better adapted to concentration. Fig. 3 shows schematic view of a satellite using PV panels and V-trough concentrators. V-trough concentrators use reflective surfaces that collect and redirect the solar radiation on the solar cells.

2.1.2. Stand alone systems

The prime objective of stand alone system was to support the farmers for their electrical demand for agricultural water pumping and for community and rural electrification [45–48]. The community schools, hospitals and other government buildings were also benefited with this technology. Arab et al. [45] have defined the efficiency of the water pumping system as the product of the efficiencies of the PV generator, of the mismatch and the motor pump assembly as

$$\eta_{sys} = \eta_{PV}\eta_{Mis}\eta_{MP} \tag{1}$$

where η_{PV} is the PV generator efficiency, defined as the ratio between the maximum electric power which can be delivered to the load and the incident power radiation on the tilted surface:

$$\eta_{PV} = \frac{P_M}{S_T A_c N_P N_S N_{MS} N_{MP}} \tag{2}$$

where S_T is the global insolation on the PV generator plane (W/m^2), A_c is the illuminated area of one solar cell (m^2), N_P is the number of cells in parallel in the PV module, N_S is the number of cells in series in a module, N_{MP} is the number of modules in parallel in the PV

Table 2
Space photovoltaic cells and their expected performances.

Cell type	AM0, 28 °C, BOL		Mass (kg/m^2)	Cost ($k/kg)
	η (%)	P (W/m^2)		
Si (200 μm)	13.5	182.3	0.55	20
High η Si (100 μm)	16.0	216.0	0.28	50
Double J (100 μm)	22.0	297.0	0.83	140
Triple J	25.0	337.5	0.85	150
Quadruple J	28.0	378.0	0.86	–

Source: Ref. [44].

Table 3
Typical PV conversion efficiencies with respect to cell temperature.

Cell type	η (%)		
	28 °C (Ref.)	58 °C ($C = 1$)	100 °C ($C \approx 1.75$)
Si (200 μm)	13.5	11.9	9.7
High η Si (100 μm)	16.0	14.2	11.6
Double J (100 μm)	22.0	20.7	18.8
Triple J	25.0	23.3	20.9

Source: Ref. [44].

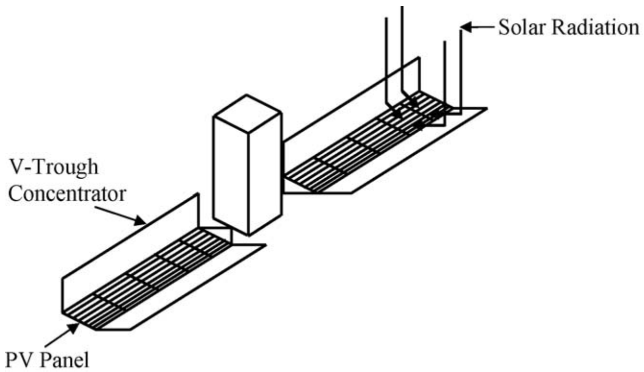

Fig. 3. Schematic view of a satellite using PV panels and V-trough concentrators [44].

generator, N_{MS} is the number of modules in series and P_M is the maximum electric power of the generator (W).

Here, η_{Mis} is the mismatch efficiency which takes into account the losses when the operation point does not coincide with the maximum power point of the PV array as

$$\eta_{Mis} = \frac{P_W}{P_M} \tag{3}$$

where P_W is the input working power of the motor pump unit. η_{MP} is the motor pump unit efficiency defined as the ratio between the output hydraulic power and the input electric power as

$$\eta_{MP} = \frac{9.81QH/3.6}{P_W} \tag{4}$$

where Q is the water flow rate (m^3/h) and H is the total pumping head (m).

Hadi et al. [48] have done experiments on a photovoltaic pumping system and reported that the average photovoltaic efficiency is 12.5% whereas the subsystem efficiency as 60 and total efficiency of the system, which is a product of the two as 8%. They defined photovoltaic efficiency (η_{PV}) as the ratio of electrical power generated to the corresponding total solar irradiance, subsystem efficiency (η_{Sub}) as the ratio between the hydraulic power and the power of solar generator. The overall system efficiency (η_{sys}) is the product of the two above said efficiencies and can be given as

$$\eta_{sys} = \eta_{PV}\eta_{Sub} = \frac{QH}{0.367 S_T A} \tag{5}$$

where

$$\eta_{PV} = \frac{VI}{S_T A} \tag{6}$$

and

$$\eta_{Sub} = \frac{QH}{0.367 VI} \tag{7}$$

Here, A is the area of the photovoltaic panel (m^2), V is the voltage output (V), I is the current output (A) of the photovoltaic panel, Q is the water flow rate (m^3/h) and H is the total head delivery (m).

The subsystem efficiency also takes care of the efficiencies of motor, pump and DC–DC converter. Fig. 4 shows a solar water pumping system as an example of stand alone system.

2.1.3. Grid connected PV systems

Attempts have already been made to connect a series of PV panels to generate a higher amount of electricity that can directly be given to the grid [49–52]. To analyze the performance of a grid connected PV system, certain parameters are important; they are yields (reference, array and final), losses (array capture and system losses), PV and inverter efficiencies and performance ratio. Mondol et al. [52] have defined various above said terms as daily array ($Y_{a,d}$) and final ($Y_{f,d}$) yield which result in

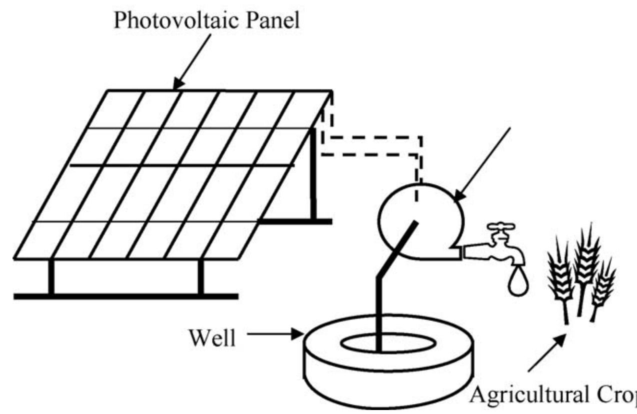

Fig. 4. Schematic diagram of an agricultural solar water pumping stand alone system.

$$Y_{a,d} = \frac{E_{DC,d}}{P_{PV,rated}} \tag{8}$$

and

$$Y_{f,d} = \frac{E_{AC,d}}{P_{PV,rated}} \tag{9}$$

The monthly average daily array yield ($Y_{a,m}$) is defined as

$$Y_{a,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{a,d} \tag{10}$$

A similar expression is used to calculate the monthly average daily final yield ($Y_{f,m}$).

The monthly and system efficiencies can be calculated by taking an average of daily PV and system efficiencies over a month. This can also be done by using the monthly total DC and AC outputs and monthly total in plane insolation as

$$\bar{\eta}_{PV,m} = \left(\frac{1}{N}\sum_{d=1}^{N}\eta_{PV,d}\right) = \left(\frac{\sum_{d=1}^{N} E_{DC,d}}{\sum_{d=1}^{N} S_T A}\right) \tag{11}$$

$$\bar{\eta}_{sys,m} = \left(\frac{1}{N}\sum_{d=1}^{N}\eta_{sys,d}\right) = \left(\frac{\sum_{d=1}^{N} E_{AC,d}}{\sum_{d=1}^{N} S_T A}\right) \tag{12}$$

The monthly inverter performance can be calculated in terms of monthly inverter efficiency as

$$\bar{\eta}_{IN,m} = \left(\frac{1}{N}\sum_{d=1}^{N}\eta_{IN,d}\right) = \left(\frac{\sum_{d=1}^{N} E_{AC,d}}{\sum_{d=1}^{N} E_{DC,d}}\right) \tag{13}$$

The performance ratio (PR) is the rating most used to describe the energy transformation in a grid connected PV system. It also indicates that how close a PV system approaches ideal performance during real operation. It can be defined as the ratio of daily final yield ($Y_{f,d}$) to daily reference yield ($Y_{r,d}$) as

$$PR_d = \frac{Y_{f,d}}{Y_{r,d}} = \frac{Y_{f,d} S_{STC}}{S_{T,d}} \tag{14}$$

The monthly average daily AC performance ratio ($PR_{AC,m}$) can be defined as

$$PR_{AC,m} = \frac{1}{N}\sum_{d=1}^{N} PR_{AC,d} = \left(\frac{\sum_{d=1}^{N} E_{AC,d}}{\sum_{d=1}^{N} S_{T,d}}\right)\left(\frac{S_{STC}}{P_{PV,rated}}\right) \tag{15}$$

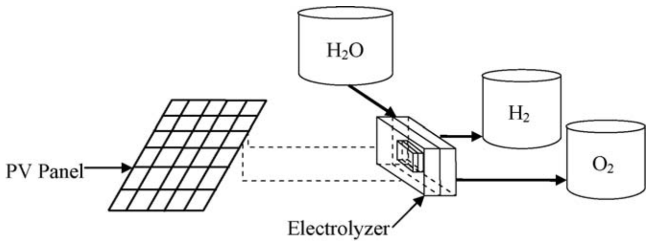

Fig. 5. Schematic diagram of a photovoltaic hydrogen production system.

A similar expression can be used to calculate DC performance ratio ($PR_{DC,m}$).

Based on above said parameters, Mondol et al. [52] have examined the performance of a 13 kWp grid connected photovoltaic system in Northern Ireland and found that The monthly average daily PV, system and inverter efficiencies varied from 4.5 to 9.2%, 3.6 to 7.8% and 50 to 87%, respectively. The annual average PV, system and inverter efficiencies were 7.6, 6.4 and 75%, respectively. The monthly average daily DC and AC performance ratios ranged from 0.35 to 0.74 and 0.29 to 0.66, respectively. The annual average monthly AC performance ratios for the three years were 0.60, 0.61 and 0.62, respectively.

2.1.4. Hydrogen production

PV panels can be utilized to produce hydrogen by electrolysis of water using the electricity produced by it [53–56]. It needs a higher and extensive research in this area as the hydrogen produced by this technology is not cost effective as the PV technology is costly. The end product of the electrolysis was also oxygen. Fig. 5 shows a schematic diagram of hydrogen production system that uses photovoltaic technology. The electrolysis of distilled water using electricity produced by the PV panel takes place in electrolyzer unit and produces hydrogen and oxygen as the end product as shown in the same figure. Yilanci et al. [56] have defined the performance of a solar based hydrogen production system based on energy and exergy analysis of PV, charge regulators, inverter and electrolyzer which is given in Table 4. They calculated the exergy efficiency of PV panel between a minimum of 9.8% and a maximum of 11.5%, charge regulator between a minimum of 85% and a maximum of 90%, inverter efficiency between a minimum of 85% and a maximum of 90% and the electrolyzer efficiency as 52%. These results along with energy efficiency of each component are also summarized in the same table. Based on the exergy and energy efficiencies of each component one can calculate the overall exergy and energy efficiencies of the system by taking the product respective efficiencies of each components. Using each component's exergy and energy efficiency the exergy and energy efficiency of the solar hydrogen production system can be defined, respectively as

$$\psi_{sys} = \psi_{PV}\psi_{CR}\psi_{IN}\psi_{EL} \quad (16)$$

and

$$\eta_{sys} = \eta_{PV}\eta_{CR}\eta_{IN}\eta_{EL} \quad (17)$$

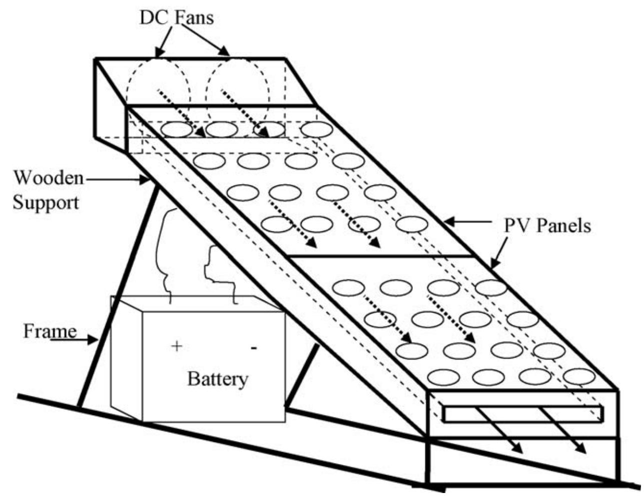

Fig. 6. Schematic diagram of hybrid PV/T air collector.

Referring to Table 4 and by using Eqs. (16) and (17), the minimum and maximum exergy efficiencies of the system are determined as 3.68 and 4.32% and the minimum and maximum energy efficiencies as 4.53 and 5.02%, respectively.

2.1.5. Other applications

Another application of the PV technology is to use the PV panels on the roof top of cars to harvest the solar energy and utilize the electricity produced to charge the batteries which further runs an electrical motor to power the car [57]. This technology is still under development and can result in a future generation automobiles. The street lights, traffic signals, solar lanterns, calculators, watches, DC fans, DC motors, inverters, etc. are some other applications of PV technology.

2.2. Photovoltaic thermal (PV/T) applications

The PV/T systems came into existence with an idea to utilize the thermal energy of the sun along with the electricity. Use of thermal energy also improves the energy and exergy efficiency and helps to maintain a good electrical efficiency of the PV system throughout its operation. The thermal energy available on the PV surface can be utilized for low potential works such as water and air heating. Further, the hot water/air can be utilized for various applications for example, to heat up living space, greenhouse, solar dryers, solar stills, etc. In the subsection now we will discuss about the PV/T air and water collectors and their applications. Some potential applications of the technology are also discussed in brief at the end of this section.

2.2.1. PV/T air collector

A schematic diagram of hybrid photovoltaic/thermal (PV/T) air collector is shown in Fig. 6. It has an air duct below the PV panels and DC fans to blow air in the air duct. The system is mounted on a

Table 4
Average energy and exergy efficiencies of system components.

Components	Energy efficiency equation	Exergy efficiency equation	Energy efficiency (%)	Exergy efficiency (%)
PVs	η_{PV} = (monthly power production/$S_T A$)	$\psi_{PV} = \frac{V_{oc}I_{sc}-[(V_{oc}I_{sc}-V_m I_m)+\dot{Q}(1-(T_{amb}/T_{cell}))]}{\dot{E}x_{solar}}$	11.2–12.4	9.8–11.5
Charge regulators	η_{CR} = (DC power output/DC power input)	ψ_{CR} = (DC power output/DC power input)	85–90	85–90
Inverter	η_{IN} = (AC power output/DC power input)	ψ_{IN} = (AC power output/DC power input)	85–90	85–90
Electrolyzer	$\eta_{EL} = \frac{\dot{m}_{H_2} \cdot HHV_{H_2}}{\text{power input}}$	$\psi_{EL} = \frac{\dot{E}x_{output}}{\text{power input}} = \frac{\dot{E}x_{H_2}+\dot{E}x_{O_2}}{\text{power input}}$	56	52

HHV: higher heating value of hydrogen.
Source: Ref. [56].

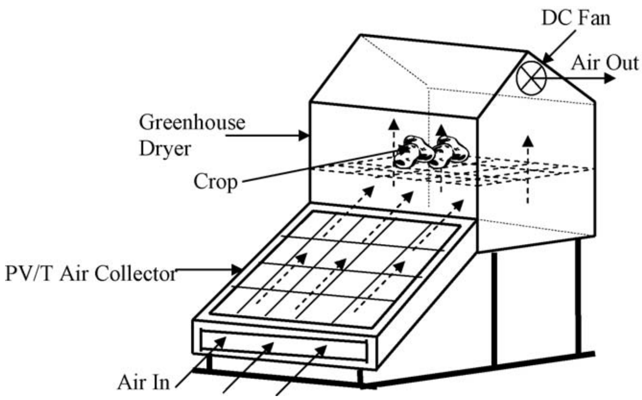

Fig. 7. Schematic diagram of a photovoltaic air heater coupled with a greenhouse dryer.

wooden support which is further supported by a frame. The PV/T system can be used for various applications such as solar drying and food process industries [58]. A greenhouse dryer is used to dry the agricultural products using solar energy so that it can be stored for longer duration. If a PV/T air collector is attached to the dryer, this would add more thermal energy to it and the drying process would be faster. Fig. 7 shows the greenhouse dryer coupled with the PV/T air heater. A DC fan is empowered by the electricity generated by it whereas the heat (thermal energy) is also utilized to dry the agricultural crop as discussed earlier. The direction of the air flow is also shown in the same figure. The greenhouse drying can be done for both natural as well as forced mode of air circulation. Table 1 shows the thermal efficiency of some PV air collectors. It is clear from the Table 1 that by increasing the area inside the air duct by placing a thin metal sheet or fins or ribs the thermal efficiency gets better [43].

Another application of this technology is to heat the living space. The space heating application further involves two types and they are transparent PV panels mounted on the roof of a building and PV panels installed on the ground and coupled with a living space. The former is an example of natural mode of heating a building as the transparent PV modules allow solar radiations to get inside the building and heat the living space (Fig. 8) where as the latter is en example of forced mode as it uses a blower or a small fan to circulate the room air to come in contact with the collector and get heated (Fig. 9).

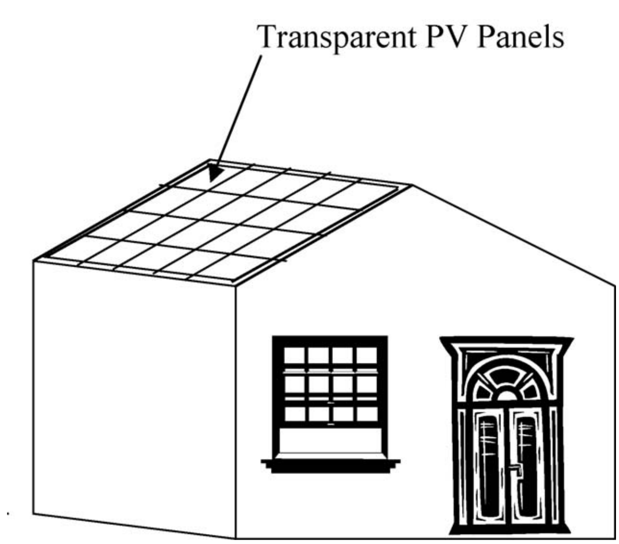

Fig. 8. Roof top mounted transparent PV panels for space heating application.

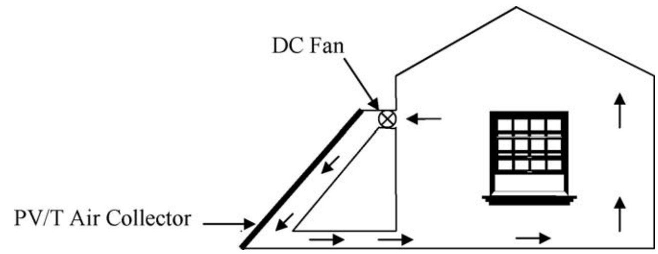

Fig. 9. Schematic diagram of photovoltaic air heater coupled with a living space.

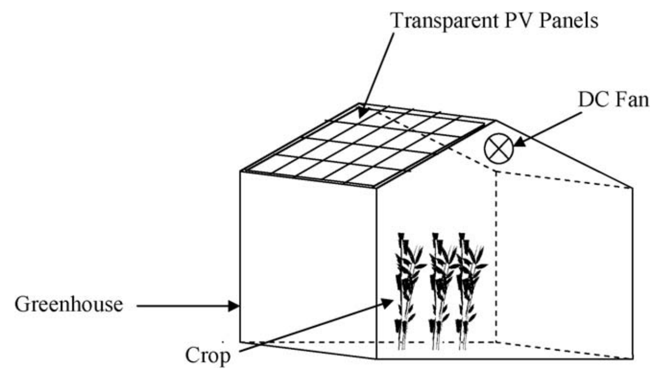

Fig. 10. A typical greenhouse with a transparent PV panel mounted on the roof.

A PV/T air heater as shown in Fig. 6 can be coupled with a building or living space (as shown in Fig. 9). Charalambous et al. [42] suggested that the building integrated PV/T collectors are most suited for low climatic conditions to lower the temperature of the PVs and supply the hot air for space heating. The greenhouse technology is also benefited with the use of the PV applications in order to maintain controlled environment in terms of temperature and humidity.

Fig. 10 shows a typical greenhouse using a transparent photovoltaic panel mounted on the roof for its electrical demand to run electrical motors, fans and blowers to maintain the desirable environment suitable for the crop production. Transparent panel also allows solar radiation to cross it and heat the greenhouse environment. The energetic and exergetic analysis of PV/T system (air collector) is discussed in Section 3. The same analysis is also done for PV systems for comparison in the same section.

2.2.2. PV/T water collector

Similar to the air collectors, water collectors are used to heat up the water for various domestic and industrial applications. The domestic water heater generally uses flat plate collectors in parallel connection and run automatically with the thermo-siphon action where as the industrial water heater uses a number of flat plate collectors in series and the thermo-siphon action does not work in this case and hence it uses a photovoltaic driven water pump to maintain a flow of water inside the water collector. A schematic diagram of a PV/T water collector is shown in Fig. 11. A DC water pump is used to circulate water as the two flat plate collectors are connected in series.

He et al. [59] defined the performance of a PVT collector by a combination of efficiencies, thermal efficiency (η_{th}) and electrical efficiency (η_e). They are, respectively, the ratio of the useful thermal gain and electrical gain of the system to the incident solar irradiation on the collector's aperture within a given period. The sum of the two gives the total efficiency (η_{total}) that is commonly used to assess the overall performance. They also reported a daily thermal efficiency of around 40% of the system. An expression of

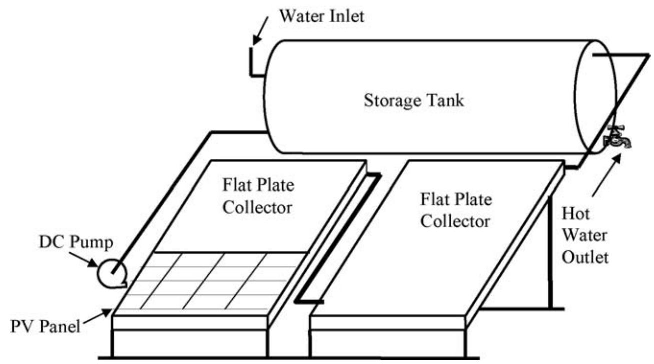

Fig. 11. Schematic diagram for hybrid photovoltaic solar water heater.

total efficiency can be given as

$$\eta_{total} = \eta_{th} + \eta_{e} \tag{18}$$

Alternatively, by considering electrical energy as a high-grade form of energy gain, they defined energy-saving efficiency η_f as

$$\eta_f = \frac{\eta_e}{\eta_P} + \eta_{th} \tag{19}$$

where η_P is the power plant efficiency which is equal to 38%.

Several researchers [60–62] have also defined a combined photovoltaic thermal efficiency same as He et al. [59] by adding thermal and electrical efficiencies of the PV/T system. Chow et al. [63] has done an experimental study of facade-integrated photovoltaic/thermal water-heating system and found the thermal efficiency as 38.9% at zero reduced temperature and the corresponding electrical efficiency as 8.56% during the late summer of Hong Kong. They compared both forced as well as natural mode of water circulation and found that the latter is more preferable and suggested that the system can serve as a water pre-heating system. Ji et al. [64] has done a theoretical study on PV/T water collector by comparing the annual performance of a film cell and single silicon cell modules and reported that they give 58.9 and 70.3% overall thermal efficiency, respectively which are better than the conventional solar collector performance. Furthermore, Ji et al. [65] have done experiments on a flat-box aluminum-alloy photovoltaic and water-heating system designed for natural circulation and found its daily electrical efficiency as about 10.15%, the characteristic daily thermal efficiency exceeded 45%, the characteristic daily total efficiency above 52% and the characteristic daily primary-energy saving was up to 65%.

Similar to the PV/T air collectors, water collectors are also used to heat the living space by circulating the hot water in the water jackets around the walls of a room (Fig. 12). Heat dissipates from the jacket and gives warmth to the room and the living space. One advantage of heating of living space using water as the media is that it can last for a longer period as the heat storage capacity of water is greater than that of air.

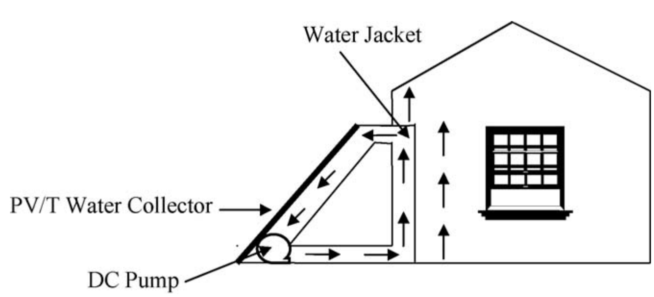

Fig. 12. Schematic diagram of heating application of PV/T water heater.

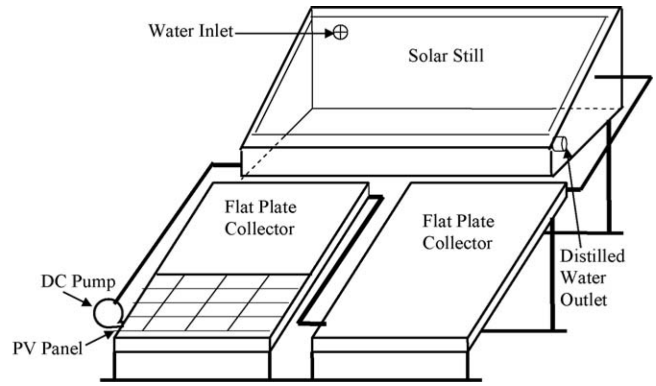

Fig. 13. Schematic diagram of space an active solar still.

Another application of PV/T water collector is solar stills. Solar stills are used to purify or distill water and it is beneficial for the areas where brackish water has salinity more than 10,000 ppm. This distilled water can be used in various industries like battery industry, hydrogen production industry etc. Solar stills are coupled with the photovoltaic water collector and uses thermal energy to heat water and electrical to circulate water through a water pump. This system is known as hybrid solar still and gives a reasonably higher thermal efficiency [66]. A schematic diagram of an active solar still is given in Fig. 13.

2.2.3. Other applications

Fish growing (aqua culture) require a specific environment in terms of water temperature. A PV/T water collector coupled with a greenhouse water pond can be beneficial for the growth of sweet water fish in order to maintain the desired temperature of water in the pond the PV operated water collectors can be used. To circulate water in the flat plate collector a photovoltaic water pump can be used. Other types of PV/T applications systems may be employed in wine distilleries, medicine industries, dairy industries, etc. where ever active distillation is required.

In all the above mentioned applications PV panels are used hence a performance analysis is important in order to ensure its efficiency from the various systems. In the next section, performance analysis of PV and PV/T system is discussed based on energy and exergy efficiencies.

3. Performance analysis through energy and exergy efficiencies

The exergetic performance of photovoltaic system has been done by some researchers [67–71]. They have defined the exergy efficiency of the systems in different ways by considering PV or PV/T as a part of the system. In this section, we will discuss the performance analysis of PV and PV/T systems based on their exergy efficiency.

3.1. PV systems

The energy of a photovoltaic system depends on two major components namely electrical energy and thermal energy. While the electricity is generated by photovoltaic effect the photovoltaic cells also get heated due to the thermal energy present in the solar radiation. The electricity (electrical energy) generated by a photovoltaic system is also termed as the electrical exergy as it is the available energy that can completely be utilized in useful purpose. Since the thermal energy available on the photovoltaic surface is not utilized for useful purpose in case of PV systems only and hence called as heat loss to the ambient. However this thermal energy can be used for useful purposes in case of PV/T systems. The energy efficiency of a PV system can be defined as a ratio of total

energy to the total solar energy falling on the photovoltaic surface and can be given as

$$\eta = \frac{En}{S_T A} = \frac{V_{oc} I_{sc} + \dot{Q}}{S_T A} \tag{20}$$

Solar cell power conversion efficiency (η_{pc}) can be defined as a function of actual current, actual voltage and solar irradiance as

$$\eta_{pc} = \frac{V_m I_m}{S_T A} \tag{21}$$

where S_T represents hourly measured total solar irradiation and A is the area of the solar cell. This efficiency is also called electrical (exergy) efficiency.

The solar power conversion efficiency can also be defined in terms of fill factor (FF) as

$$\eta_{pc} = \frac{\mathrm{FF}\, V_{oc} I_{sc}}{S_T A} \tag{22}$$

where FF = $V_m I_m / V_{oc} I_{sc}$.

An expression for electrical (exergy) efficiency proposed by Zondag et al. [33] can be given as

$$\psi_e = \eta_{cell}[1 - 0.0045(T_{cell} - 25\,^\circ\mathrm{C})] \tag{23}$$

Joshi et al. [67] have done the performance analysis of both PV and PV/T system in terms of exergy efficiency and reported that the thermal energy due to solar radiations is actually a heat loss to the PV system where as it is a useful heat for a PV/T system. They also said that the electrical (exergy) efficiency of a PV system can be improved if the heat can be removed from the PV surface. The exergy efficiency of a system can in general be given as

$$\psi = \frac{\dot{E}x}{\dot{E}x_{solar}} \tag{24}$$

where $\dot{E}x$ is the exergy of the PV system which is mainly electrical power output of the system. Since the thermal energy gained by the system during the operation is not desirable in case of PV system, this becomes a heat loss to the system and hence needs to be subtracted from the former in order to calculate the exergy of a PV system. $\dot{E}x_{solar}$ is the exergy rate from the solar irradiance in W/m^2 which can be given as [67]:

$$\dot{E}x_{solar} = \left(1 - \frac{T_{amb}}{T_{sun}}\right) S_T A \tag{25}$$

An expression for exergy efficiency for the PV system can be given as

$$\psi_{PV} = \frac{V_m I_m - (1 - (T_{amb}/T_{cell}))\dot{Q}}{(1 - (T_{amb}/T_{sun}))S_T A} \tag{26}$$

where

$$\dot{Q} = h_{ca} A (T_{cell} - T_{amb}) \tag{27}$$

and

$$h_{ca} = 5.7 + 3.8v \tag{28}$$

The convective (and radiative) heat transfer coefficient from photovoltaic cell to ambient, h_{ca}, can be calculated by considering wind velocity (v), density of the air and the surrounding (ambient) conditions [68].

The exergy rate of solar irradiance can also be calculated by using Petela's [8] formula and given as

$$\dot{E}x_{solar} = \left[1 + \left(\frac{1}{3}\right)\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \left(\frac{4}{3}\right)\left(\frac{T_{amb}}{T_{sun}}\right)\right] S_T A \tag{29}$$

By substituting $\dot{E}x_{solar}$ from Eq. (29) in Eq. (24), the exergy efficiency of PV system becomes

$$\psi_{PV} = \frac{V_m I_m - (1 - (T_{amb}/T_{cell}))\dot{Q}}{[1 + (1/3)(T_{amb}/T_{sun})^4 - (4/3)(T_{amb}/T_{sun})]S_T A} \tag{30}$$

3.2. PV/T systems

Unlike PV systems, PV/T system uses the thermal energy available on the PV panel and this time the thermal energy gain can be utilized as a useful energy and hence, the exergy of the PV/T system becomes the sum of the electrical exergy and thermal exergy of the system and the exergy efficiency can be defined as

$$\psi = \frac{\dot{E}x}{\dot{E}x_{solar}} = \frac{\dot{E}x_e + \dot{E}x_{th}}{\dot{E}x_{solar}} \tag{31}$$

By substituting the values of $\dot{E}x$ and $\dot{E}x_{solar}$ in Eq. (31), the exergy efficiency of a PV/T system results in

$$\psi_{PV/T} = \frac{V_m I_m + (1 - (T_{amb}/T_{cell}))\dot{Q}}{(1 - (T_{amb}/T_{sun}))S_T A} \tag{32}$$

By substituting $\dot{E}x_{solar}$ from Eq. (29) in Eq. (31), the exergy efficiency of PV/T system becomes

$$\psi_{PV/T} = \frac{V_m I_m + (1 - (T_{amb}/T_{cell}))\dot{Q}}{[1 + (1/3)(T_{amb}/T_{sun})^4 - (4/3)(T_{amb}/T_{sun})]S_T A} \tag{33}$$

The above-mentioned analysis has been done considering a natural mode of ambient air circulation over the PV surface; however, a forced mode can also be applied by blowing air beneath the surface by means of a fan in order to remove heat at a faster rate [68].

Joshi and Tiwari [37] have also evaluated the exergy efficiency of PV/T air collector in terms of electrical and thermal exergies as

$$\psi_{PV/T} = \frac{\eta_0[1 - \beta\Delta T]S_T A + \dot{Q}[1 - (T_0 + 273)/(293 + \Delta T)]}{S_T A} \tag{34}$$

where β = 0.0045 °C, T_0 is the reference ambient temperature = 20 °C (293 K), η_0 the electrical efficiency under standard test condition and ΔT the temperature difference between ambient and the collector outlet temperature.

Fujisawa and Tani [69] have defined the instantaneous electrical exergy of a photovoltaic thermal (PV/T) hybrid collector as a product of global irradiance (S_T) and the energetic efficiency of the solar cell (η_{cell}) as

$$\dot{E}x_e = \eta_{cell} S_T = \psi_{cell} S_T \tag{35}$$

where ψ_{cell} is the exergetic efficiency of the solar cell.

They also defined the synthetic exergy of the PV/T collector as the sum of electrical and thermal exergies as follows:

$$\dot{E}x_{PV/T} = \dot{E}x_e + \dot{E}x_{th} = (\psi_e + \psi_{th}) = \psi_{PV/T} S_T \tag{36}$$

where

$$\dot{E}x_e = \psi_e S_T \tag{37}$$

and

$$\dot{E}x_{th} = \dot{Q}\eta_{Carnot} = \dot{Q}\left(\frac{T_f - T_0}{T_f}\right) = \psi_{th} S_T \tag{38}$$

Saitoh et al [70] have also calculated exergy efficiency similar to Fujisawa and Tani [69] of a hybrid PV/T solar collector that generates electricity and heat as

$$\psi_{PV/T} = \frac{\eta_{pc} S_T + \dot{E}x_{th}}{\dot{E}x_{solar}} \tag{39}$$

where

$$\dot{E}x_{\mathrm{th}} = \left(\frac{T_{\mathrm{f}} - T_0}{T_{\mathrm{f}}}\right)\dot{Q}_{\mathrm{th}} \tag{40}$$

and

$$\dot{E}x_{\mathrm{solar}} = 0.95 S_{\mathrm{T}} \tag{41}$$

where η_{pc} is the conversion efficiency, S_{T} the global irradiance (W/m^2), $\dot{E}x_{\mathrm{th}}$ the exergy from the heat (W/m^2), $\dot{E}x_{\mathrm{solar}}$ the exergy from the global irradiance (W/m^2), $\dot{Q}_{\mathrm{th}}$ the collected solar heat amount per unit time per panel area (W/m^2) and T_{f} is the supply temperature of the fluid (K).

Hepbasli [71] has also done a review on exergy analysis of several solar energy systems especially photovoltaic thermal systems and given similar expressions as taken from Fujisawa and Tani [69] and Saitoh et al. [70].

4. Case studies

In this section, we will now apply some of the models presented above to some actual data [67] sets as obtained through experiments in New Delhi, India, which is located at 77°12′E longitude and 28°35′N latitude. The test was performed from 9:00 a.m. to 4:00 p.m. on March 27, 2006 and the data measured included total solar irradiation, voltage, open-circuit voltage, current, short-circuit current, cell temperature, ambient temperature and velocity of the air just above the photovoltaic surface. The data for hourly total solar radiation and the wind velocity is measured for different places on the photovoltaic surface and an average value for both is used to calculate energy and exergy of the photovoltaic system. The uncertainty analysis of measured global radiation is done and the internal estimate of uncertainty is evaluated following Joshi [68] and it is found that the value for uncertainty for the measured global radiation is 2.23% (for details refer to Joshi [68]). The system includes two modules in series, and the area of one solar cell is 0.0139 m^2. The number of solar cells in two modules was 72. Therefore, the efficiency analysis of PV and PV/T systems for their performance assessment is done here based on some experimental data as explained above.

4.1. Case study 1: efficiency analysis of PV system

Fig. 14 shows the variation of energy efficiency given by Eq. (20) and various exergetic efficiencies introduced by Eqs. (21), (23), (26) and (30) with time of the day. The energy efficiency varies from a minimum of 33% to a maximum of 45% at 10:00 a.m. and 4:00 p.m., respectively. The exergy efficiency of PV varies from a maximum of 13.8% to a minimum of 7.8% at 4:00 p.m. and 12:00 p.m., respectively. The power conversion efficiency also called the electrical efficiency varies from 9 to 13–14% and the electrical efficiency as proposed by Zondag et al. (Eq. (23)) varies from 10.6 to 11.3%. Exergy efficiency of PV system using Petela's formula for exergy from the solar radiation varies from 8 to 14%, respectively. The difference between the energy efficiency (Eq. (20)) and the exergy efficiency (Eq. (26)) is high as expected because the former is based on the open circuit voltage and short circuit current and also considers the thermal potential available on the PV surface whereas the latter considers only actual voltage and current produced and does not include thermal potential as it is considered to be a heat loss in this case. The difference between the electrical efficiency (Eq. (23)) and other exergy efficiencies (Eqs. (26) and (30)) can also be seen clearly from the same figure as the former uses a constant value for the ambient temperature (25 °C) and hence the variation in the temperature difference between cell temperature and the ambient temperature is comparatively less than the other two cases. The power conversion efficiency (Eq. (21)) is slightly higher as compared to the exergy efficiency calculated by Eq. (26) as it uses actual current and voltage only and not the heat loss term. It also gives a good agreement with the electrical efficiency (Eq. (23)).

The difference between the exergy efficiencies given by Eqs. (26) and (30) is due to the exergy efficiency from the solar radiation as the former uses a simple approach by considering a Carnot cycle efficiency of a heat engine working between sun temperature and the ambient whereas the latter uses a correlation given by Petela [8].

4.2. Case study 2: efficiency analysis of PV/T system

Fig. 15 shows the various exergetic efficiencies given by Eqs. (32)–(34) and (39). The exergy efficiency of PV/T system using Eq. (32) varies from a maximum of 15.7 to a minimum of 11.3% at 4:00 p.m. and 12:00 p.m., respectively. Exergy efficiency using Petela's formula for PV/T system (Eq. (33)) varies between 11.6 and 16%. The exergy efficiency for PV/T, as given in Eq. (34), by [67] is 11–12% and is between 9 and 13.5%, respectively, through Saitoh et al.'s [70] model as given in Eq. (39).

The difference between the exergy efficiency calculated by Eqs. (32) and (33) are quite less as compared to the exergy efficiencies by Eq. (34) and (39). One reason could be, that both Eqs. (34) and (39) use the difference between the inlet and outlet

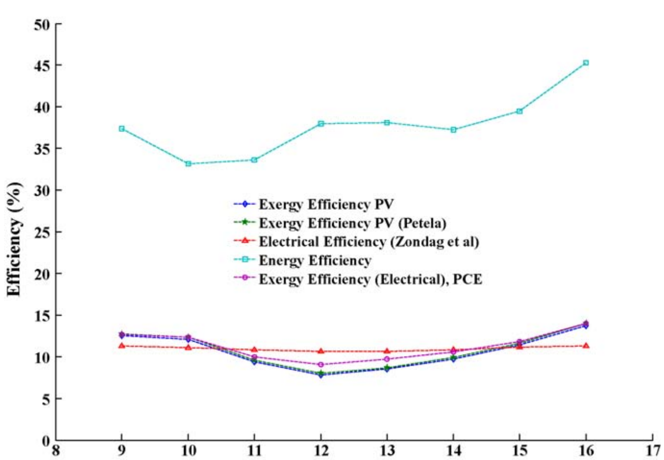

Fig. 14. Hourly variation of energy efficiency and various exergy efficiencies of a PV system.

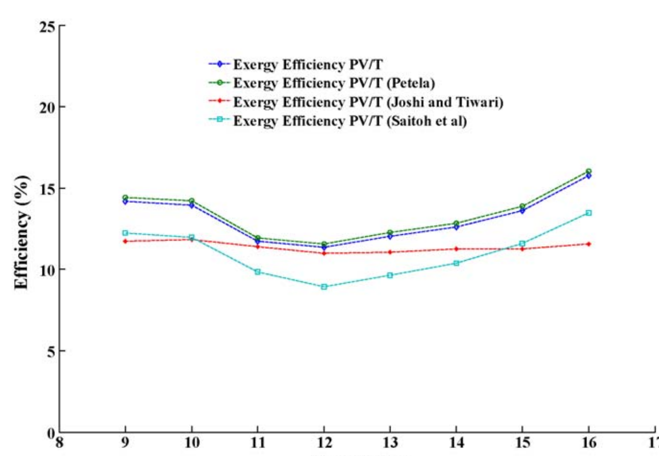

Fig. 15. Hourly variation of different exergy efficiencies of PV/T system.

temperature of the air flowing below the PV surface (air duct) where as Eqs. (32) and (33) use the temperature difference between cell and the ambient temperature. The explanation for the difference between the exergy efficiencies calculated by Eqs. (32) and (33) is similar to the one given for Eqs. (26) and (30) in Section 4.1.

It can be seen from Figs. 14 and 15 that the exergy efficiency given by various models gives good agreement with each other for PV and PV/T systems. Difference can easily be seen between exergy efficiency of PV and PV/T system as the latter is higher as expected due to the useful thermal exergy component.

In summary, the PV cells are considered a major candidate for obtaining energy from the sun, due to the fact that it can convert sunlight directly to electricity with good conversion efficiency, can provide nearly permanent power at low operating and maintenance costs and is environmentally benign and sustainable.

4.3. Case study 3: efficiency analysis of PV/T dual (air and water) systems

A comparison of PV/T dual systems, as discussed earlier, with air and water extraction is done (Figs. 16 and 17) using the thermal efficiency equations presented in Table 1 and the data for New Delhi, India climatic conditions. The thermal efficiencies of various PV/T dual systems for air heat extraction are given in Fig. 16 and for water heat extraction are given in Fig. 17. It is clear from Fig. 16 that the thermal performance of PV/T dual systems using TMS, FIN, TMS and RIB for air heat extraction is better than the PV/T dual system alone as their minimum and maximum thermal efficiencies are 8.4% and 16.4, 11.6 and 19.6%, 11 and 19.5%, and 5–12%, respectively. Using a reflector (REF), the minimum and maximum thermal efficiencies of the PV/T dual TMS, FIN, TMS and RIB further increase as 17.8 and 27.4%, 22.3 and 32%, and 22 and 32.5%, respectively.

It can be seen from Fig. 17 that the thermal performance of PV/T dual systems using TMS, FIN, TMS and RIB for water heat extraction is better than the PV/T dual system alone as their minimum and maximum thermal efficiencies become 9.2 and 21.3, 8.3 and 20.6%, 8.3 and 20.3, and 5.3–16.3%, respectively. Using a reflector (REF), the minimum and maximum thermal efficiencies of the PV/T dual system using TMS, FIN, TMS and RIB further increase as 23 and 34.2%, 22.7 and 33.7%, and 22.2 and 33.3%, respectively.

Comparing the results given in Figs. 16 and 17, it is clear that the thermal efficiency of water heat extraction is better than the air heat extraction due to the higher heat carrying capacity of water.

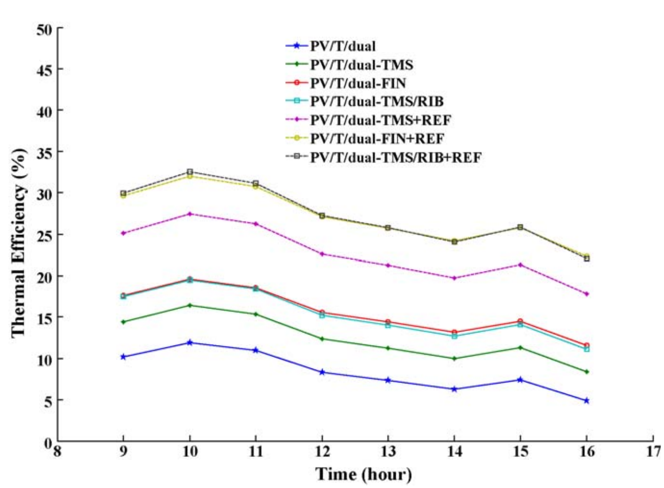

Fig. 16. Hourly variation of thermal efficiencies of PV/T dual system for air heat extraction.

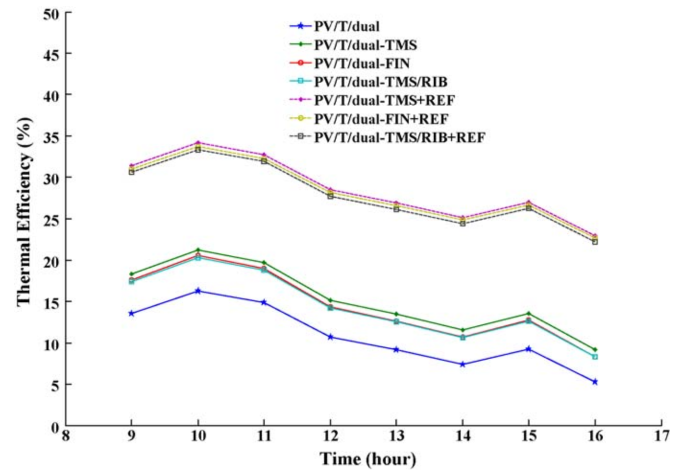

Fig. 17. Hourly variation of thermal efficiencies of PV/T dual system for water heat extraction.

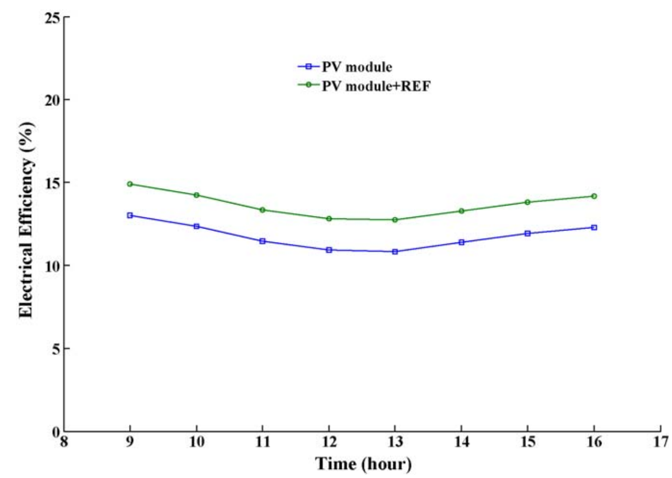

Fig. 18. Effect of reflector on the electrical efficiency of PV module.

Fig. 18 shows the electrical efficiency of PV module with and without reflector. The electrical efficiency ranges between a minimum of 10.8% and a maximum of 13% for PV module and for PV module with reflector it ranges between a minimum of 12.7% and a maximum of 15%. It is clear from the same figure that the former gives better results as the solar radiation received by PV surface is more due to reflectors.

5. Conclusions

The applications of PV and PV/T systems have been presented with details. Various thermodynamic approaches have been discussed to assess the performance based on efficiency of PV and PV/T systems. Several methods for assessing exergy efficiencies of PV and PV/T systems have been discussed and applied to an actual system. Using these formulations, differences are illustrated between PV and PV/T system's exergy efficiencies. It is suggested that exergy analysis should be used for PV system evaluations and assessments, so as to allow for more realistic modeling, evaluation and planning for PV systems. Some concluding remarks are as follows:

- Exergy efficiency of PV/T systems is more than that of PV systems as the former give useful thermal output also apart from electricity.

- By increasing the area of air/water duct (by placing a thin metal sheet or ribs or fins or a combination of the three inside the duct), the heat removal from the PV surface can be faster.
- By using reflecting surfaces, the thermal as well as electrical efficiencies can be increased as more radiations fall on the PV surface.
- The thermal efficiency of PV/T water collector is more than that of PV/T air collector due to higher density of water.

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